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Experimental testing of a masonry arch bridge model subject to increasing level of damage

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ABSTRACT: Masonry arch bridges are particularly sensitive to the bearings loss produced by scour of the streambed soil at the piers foundations. A 1:2 scaled experimental model of a masonry arch bridge was built to study the evolution of the damage mechanism related to the application of foundation movements. The model was built with handmade clay bricks and a mortar with poor mechanical properties in order to reproduce typical materials of historical constructions, and an extensive characterization of the materials has been carried out. The mid-span pier is placed on a settlement application system, expressly designed to simulate the scour effect, quantified through hydraulic flume tests performed on a further scaled down model. Damage levels of increasing intensity have been simulated through the application of pier settlements and rotations.

Experimental vibration tests were performed on the undamaged structure and after each settlement step. Both the environmental noise and the impacts of a sledge hammer were used as excitation sources. A complete dynamic identification was carried out and the variation of modal parameters at different levels of damage monitored. Moreover, the use of a testing shaker allowed investigating the non - linear behaviour of the damaged model.

INTRODUCTION

The paper presents a series of test campaigns performed on a masonry arch bridge model in the laboratory of the Department of Structural and Geotechnical engineering of the Polytechnic of Turin since 2006 to nowadays. The experimental model was mainly built to study the evolution of damage mechanisms related to the settlements of the central pier within the National Research Project (PRIN) *"Guide-lines for the surveillance and management of historical structures and infrastructures, with the aid of automatic innovative monitoring systems"*.

In the last years the model was subject to a wide gamma of characterisation tests and analyses. The paper elucidates the knowledge course that has been chosen to investigate the model and how the various tests were planned and carried out.

During the realisation of the model, a set of preliminary tests were carried out, mainly on the bridge materials. In this phase also a hydraulic flume test on a further scaled model was performed to simulate the scour effect. Two finite element (FE) models were also built in order to predict the model behaviour: a linear FE for designing vibration tests, and a non-linear one for predicting crack patterns due to the settlement application.

The second phase of testing regarded the dynamic characterisation of the bridge model at different damage steps. Nine damage steps were planned to be applied through a settlement application device. At each step a wide set of vibration tests were carried out, using different excitation sources, such as ambient vibrations, hammer impact and an electro-mechanic shaker. Through modal identification techniques, the modal parameters have been identified and, consequently, monitored during the whole experimentation. The monitoring of modal parameters supported the design of a structural health monitoring system using the outlier analysis (Worden et al. 2000; Ruocci 2010).

Instantaneous fitting techniques (Ceravolo 2004) allowed identifying punctual variations in the modal parameters during the application of the settlements (Quattrone et al. 2010).

Moreover, the forced vibration tests using a shaker allowed the detection of non-linear phenomena. Current efforts deal with the identification of non-linearity using instantaneous techniques (Ceravolo et al. 2010).

1 THE MASONRY ARCH BRIDGE MODEL

The 1:2 scaled model of the masonry arch bridge shown in Figure 1 was built in the laboratory of the Department of Structural and Geotechnical Engineering at the Politecnico di Torino. The prototype this model comes from is not a real existing bridge but was designed taking the masonry arch bridges common features, geometric proportions and historical design codes into account.

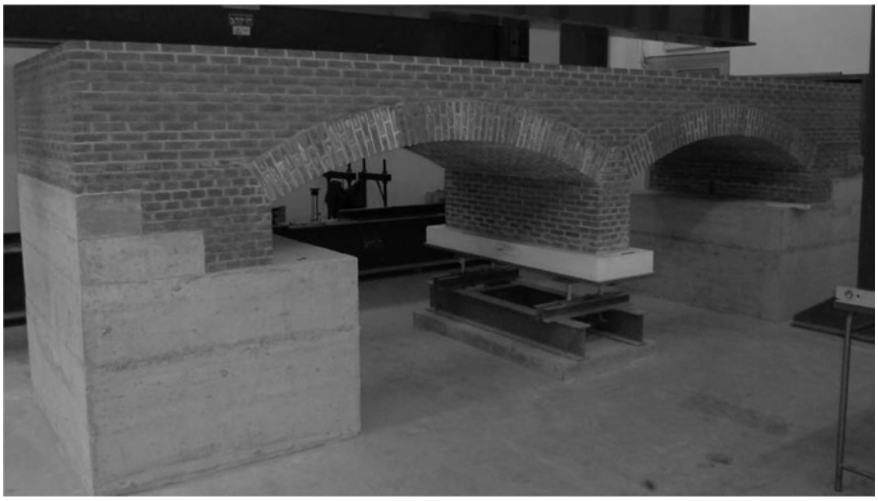

Figure 1. The scaled masonry bridge: notice the settlement application device under the central pier.

The model is a twin-arch bridge with a length of 5.90m, a width of 1.60m and it is 1.75m high. The two arches are segmental arches with a radius of 2.00m and an angular opening of 30°. Each span is 2.00m long between the supports and the thickness of the arch is equal to 0.20m. The model was built with handmade clay bricks also scaled to 130x65x30mm to respect the adopted modelling scale law. Low compressive strength elements were chosen and a mortar with poor mechanical properties was used to bound them in order to reproduce the typical materials of historical constructions.

The mid-span masonry pier, which was cut at a hypothetical middle-height section to allow the insertion of a settlement application system, is imagined to be placed inside the streambed and subjected to the scour of its foundation.

Some hydraulic flume tests were carried out on a further scaled down model of the bridge pier in order to simulate the scour effects in the lab. The foundation settlements and rotations resulting from these investigations were then replicated on the bridge model by means of the four independent screws installed at the extremities of the settlement application system. The spherical plain bearings placed at the head of the screws allow the rotations of the plate which support the central pier about axes parallel to the longitudinal and transversal directions of the bridge.

In order to simulate the streambed material surrounding the foundation of the central pier, a polystyrene mould was introduced. In this way a polystyrene layer interfaces the pier and the settlement application device and a polystyrene ring surrounds the pier.

2 PRELIMINARY STUDIES

The experimental investigations carried out on the masonry arch bridge model were divided in two different sessions. In the first session most of the efforts were addressed to reduce the high uncertainties referred to the material properties and the structural behaviour of this complex structure. Several destructive tests were performed on samples collected during the model construction in order to estimate the mechanical properties of the masonry material. The estimated parameters were then introduced in a numerical model of the bridge to obtain a preliminary calculation of the modal parameters. The information acquired in these initial analyses was helpful to plan the following dynamic tests and to interpret the first results of the modal identification. In this phase also hydraulic tests on a reduced model of the central pier were carried out in order to quantify the settlement to be applied.

2.1 *Material characterisation tests*

Several tests were carried out in order to characterise the mechanical properties of the mortar and of the masonry used to build model.

The characterisations tests on the mortar samples were performed following the prescriptions proposed by the European standard code EN 998-2:2003 adapted to take in account the scaled measure of bricks. The collected samples belong to the M2.5 class of the European standard code EN 998-2:2003 which is one of the poorest in terms of mechanical properties.

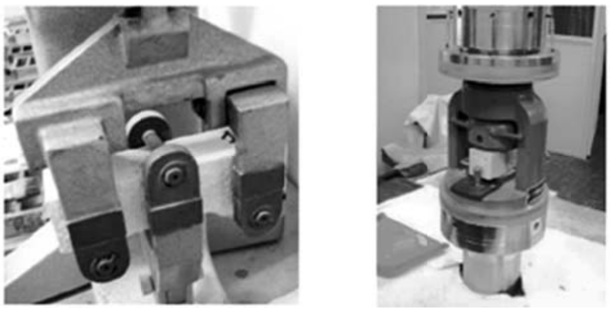

Figure 2. Tests carried out on mortar samples.

The characterisations tests on the masonry samples were performed following the prescriptions proposed by the European standard code UNI EN 1052-1, EN 1052-3:2002 and the American standard code ASTM E 518-02. The masonry samples were adapted in order to resemble the shape of required test specimens while the testing procedures were followed strictly. The destructive tests performed on the masonry samples were:

- axial compression on cubic samples;
- diagonal compression on cubic samples;
- shear test on masonry triplets;
- four points bending test on a segment of arch.

Figure 3. Tests conducted on the masonry samples.

Table 1. Results from the compressive tests, diagonal tests, shear tests and four point bending tests.

Test	μ [N/mm2]	σ [N/mm2]
Compressive tests: tensile strength	4.278	0.354
Compressive tests: Young modulus E	1451	472
Diagonal tests: tensile strength	0.304	0.088
Diagonal tests: shear strength	0.430	0.125
Diagonal tests: shear Young modulus G	940	436
Shear tests (0.1 kN pre-compression): shear strength	0.794	0.301
Shear tests (0.5 kN pre-compression): shear strength	1.013	0.188
Four points bending tests: R modulus of rupture	0.22	//

2.2 *Flume tests*

The hydraulic model was designed scaling the pier dimensions down so that the ratio between the length of the bridge and the width of the pier was maintained. The bottom section of the pier scaled model was connected with a hypothetic foundation base. The rectangular foundation was dipped into the bed material, whose uniform mean diameter was 0.80 mm, while the pier was hung up but not allowed to move during the flume tests.

The evolution of the soil profile produced by the induced scour was periodically monitored through a laser scanner acquired by a digital camera. The images taken during the tests were then automatically processed to define the portion of the foundation lateral face not covered by the bed material at each time step. The corresponding portion on the arch bridge model was freed from the polystyrene ring surrounding the bottom part of the pier to simulate the reduction of the lateral restrain at the foundation base.

Also the undermining effects were experienced in the flume tests, especially when the foundation base was not excessively dipped in the bed material. The erosion of the soil underneath the foundation, and consequently the loss of its bearing action, is simulated in the experimental model through the settlements application device previously described.

2.3 *Numerical models*

A 3D numerical model of the arch bridge was realised in the ADINA Finite Element package to estimate and assimilate modal parameters. The purpose was to better understand the dynamic behaviour of the structure and to plan accurately the following vibration analyses. In fact, the selection of the sensors location must be assessed carefully in order to allow a suitable resolution in the mode shapes for the highest number of identified modes.

The model consists mainly in solid elements and spring elements able to simulate the polystyrene layer and the settlement application device. The mechanical properties have been inherited from the material characterisation tests. The model is subdivided into a series of elements groups, where each group includes all those finite elements which share common mechanical features or structural functions.

In order to predict cracks locations, a numerical model of the masonry arch bridge (Invernizzi et al. 2009) was built in the DIANA FE package which was able to simulate the non-linear behaviour of masonry. The FE package implemented a smeared cracking model which incorporates a tension cut-off, tension softening and shear retention. After the results of non-linear analysis, it was decided to add masses at the top of the central pier so as to take in account the weight of the missing part of the pier and to partially compensate the arch effect developed by massive abutments.

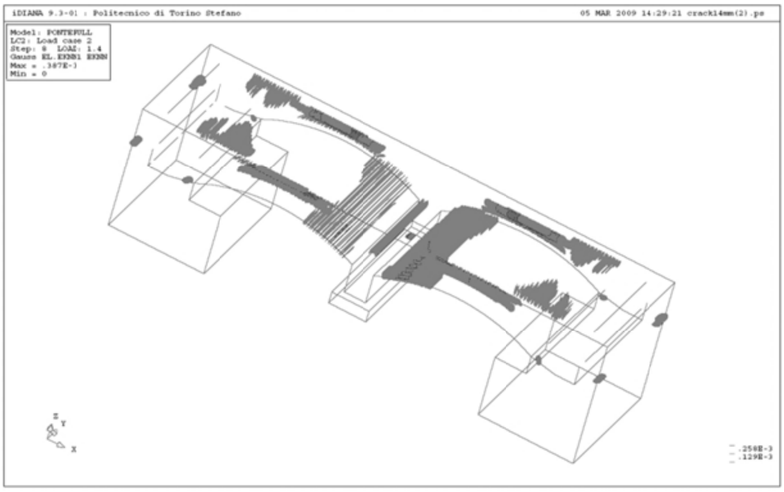

Figure 4. Non-linear model: smeared crack pattern with an applied settlement of 14 mm.

3 EXPERIMENTAL TEST

3.1 *Experimental test program*

As previously stated, the main objective of the experimental test was to determine the capability of a structural health monitoring system, based mainly on dynamic measures, to detect the occurring of damage (such as scour at the bridge pier foundation). In this framework, dynamic testing ensures to identify a set of parameters to be monitored. A sensitivity analysis has been carried out on the parameters to choose the most reliable to detect the damage.

Several damage steps have been applied to the structure in accordance with hydraulic flume tests as shown in Table 2.

Table 2. Damage steps, middle pier settlement, pier rotation, polystyrene removed.

Experimental campaign	Damage steps	Settlement [mm]	Rotation [rad]	Polystyrene
1st campaign	Healthy State (HS)	0	0	0%
2nd campaign	DS1	0	0	18%
	DS2	0.25	0	25%
	DS3	1	4.21E-04	37.5%
	DS4	2.25	1.01E-03	47%
3rd campaign	DS5	2.25	1.23E-03	56%
	DS6	2.8	1.23E-03	72%
	DS7	3.6	1.27E-03	81%
	DS8	4.7	1.30E-03	91%
	DS9	7.6	1.28E-03	100%

Table 3. Experimental tests timeline.

	Time	Step	Excitation	Measurements
1st campaign	October 2008	HS	AV, IH	ACC, SG, T, OPT
	November 2008	HS	AV, IH	ACC, SG, T, OPT
	January 2009	HS	AV, IH	ACC, SG, T, OPT
	February 2009	HS	AV, IH	ACC, SG, T, OPT
	March 2009	HS	AV, IH	ACC, SG, T, OPT
2nd campaign	April 2009	HS (applied masses)	AV, IH	ACC, SG, T, OPT
		DS1	AV, IH, S	ACC, SG, T, OPT
		DS2	AV, IH, S	ACC, SG, T, OPT
		DS3	AV, IH, S	ACC, SG, T, OPT
		DS4	AV, IH, S	ACC, SG, T, OPT
3rd campaign	September 2010	HS (post-relaxation)	AV, IH, S	ACC, SG, T, OPT
		DS5	AV, IH, S	ACC, SG, T, OPT
	October 2010	DS6	AV, IH, S	ACC, SG, T, OPT
		DS7	AV, IH, S	ACC, SG, T, OPT
		DS8	AV, IH, S	ACC, SG, T, OPT
		DS9	AV, IH, S	ACC, SG, T, OPT

Table 3 shows the timeline of the experimental tests. Different excitation sources were applied to the bridge model: ambient vibrations (AV), impact hammer (IH) and a shaker (S). Several physical quantities were monitored under the different excitations: acceleration measurements (ACC), strain deformation (SG and OPT) and temperature (T).

The experimental test involved three different experimental campaigns. The first campaign regarded the undamaged structure (October 2008 - March 2009): an extensive set of dynamic tests was carried out on the bridge model in order to characterise its "healthy" state (HS). Monitoring of dynamical properties of the bridge showed a decrease in the structure stiffness through the whole campaign. This may be due to the development of some rheologic phenomena, like the concrete blocks creep or the mortar shrinkage, leading to strains incompatible with the stiffness of the arch barrels, might have produced a partial detachment between the masonry abutments and the arch barrels.

The second campaign (April 2009) started after the application of additional masses on the central pier, in order to take in account the weight of the missing part of the pier. In the same campaign the first four settlement steps were applied on the upstream side of the pier. In addition, parts of the polystyrene ring were removed at each step to simulate the erosion of streambed around the foundation accordingly to hydraulic flume tests. Dynamical tests were conducted in correspondence of each settlement step.

During the latter campaign (September 2010 - October 2010) five further settlement steps were applied. In this phase the removal of the polystyrene ring continued until all the polystyrene was removed.

3.2 *Experimental setups*

Dynamical vibration tests require a careful identification of an optimal sensor location.

In order to achieve a good mode shapes resolution, a heuristic approach was employed. The arch barrels were subdivided in 11 segments whose ends were assumed as measuring points for both the edge and the middle lines. Other 6 positions at the springing sections of the pier were materialised to capture the longitudinal displacements. The 4 mid-span sections of the arch barrels lateral faces and the 2 pier frontal faces were considered for the lateral and torsional modes. Finally, the 2 positions on the longitudinal spandrel walls at the middle section of the deck were added to identify the vertical modes.

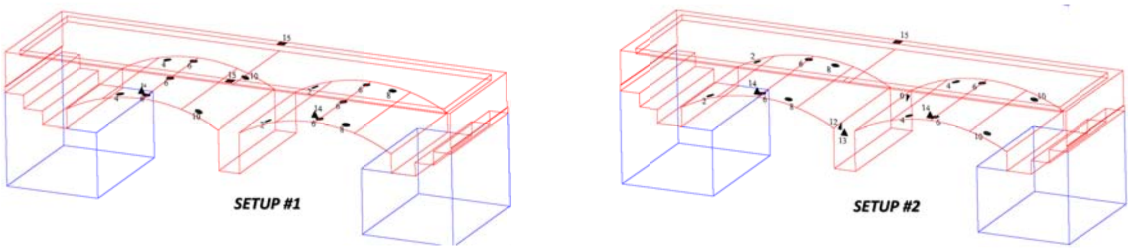

Figure 5. Experimental setups for vibration tests.

The sampling frequency was fixed to a value of 400 Hz to acquire the signals produced by both ambient noise and impact hammer excitations, using an instrumented hammer. A 180 seconds time laps was adopted for the ambient noise acquisitions. Several impacts were acquired in a 60 seconds time, even if only one impact per acquisition was used in the dynamic identification. The hammer impacts were applied in the same sensors positions along the longitudinal, transversal and vertical directions of the bridge model in order to excite properly all the modes estimated by the numerical modal analysis. Two setups were used for each vibration tests in order to capture the higher number of natural modes. Each setup consisted of 18 channels leading to 36 instrumented positions.

Forced vibration tests were performed by using a shaker TIRA TV 51220, capable to supply a rated peak force of 200 N. The force applied was acquired by using a mechanical impedance sensor PCB Piezotronics 288D01 (measurement range ±222.4 N pk). Five type of excitation tests were carried out:

- random: random excitation in a 10-100 Hz band,
- sweep sine: linear chirp from 10 to 100 Hz,
- shock: impulsive excitation,
- resonance: sine excitation at resonance frequencies,
- sine: sine excitation from 10 to 100 Hz, with 1 Hz resolution.

3.2.1 *Accelerometers*

The selected sensors for the dynamic tests performed on the structure were capacitive accelerometers. The employed dynamic acquisition system was composed by a set of 18 monoaxial PCB

Piezotronics accelerometers with a sensitivity of 1V/g, a measurement range of ±3g, a broadband resolution of 30 μg and a weight of 17.5g. The accelerometers were connected through coaxial cables to the LMS Difa-Scadas data acquisition system which provided also the signals amplification. The acquired signals were recorded on the hard drive of a laptop computer interfaced with the data acquisition system and running a specific signal acquisition software.

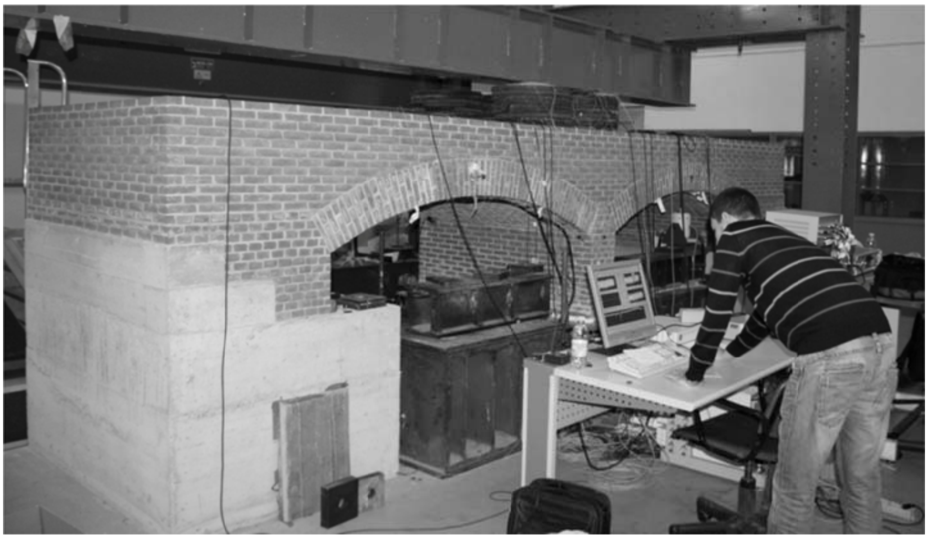

Figure 6. Accelerometers setup with acquisition system.

3.2.2 *Strain gauges*

The responses of the arch barrels to the settlements application were measured by means of a set of 16 120 Ω resistive strain gages 160mm long and 10mm wide. The length of the strain gages allowed to cross at least five bricks and thus to obtain a representative information of the masonry behaviour. The transducers were divided into two sets and were uniformly distributed on the intrados of the arch barrels at the upstream side of the bridge model. As expected from the numerical analyses, the settlement application led to tensile strains in the central portion of the bridge and compressions in the lateral parts. The distribution of the strains throughout the first three steps resulted unchanged and a progressive increase of the deformations was recorded.

3.2.3 *Optical fibres*

Fiber Optic technology is widely used to measure different structural quantities. In particular, Fiber Bragg Gratings (FBGs) are simple sensing elements, which can be photo-inscribed into a silica fiber and exploit all the advantages normally attributed to fiber sensors. They are suited to measure strain to a 1 με resolution and to operate also in hostile environments. The strain sensors employed in this work are based on the so-called ‘patch sensors’ technology (Bassam and Ansari 2008).Twelve patch sensors were glued directly on the structure, in order to measure the strain in correspondence of the masonry joints. The measured reduction in the positive strain moving from the upstream to the downstream side of the bridge agrees with the results of the numerical analyses. However, the most encouraging result for a future early warning application on real bridges was provided by the sensor glued along the vertical direction on the bridge pier. This sensor was able to detect the decompression of the pier due to the removal of the base support from the first step application. In Figure 7 the cumulative strain produced by the progressively induced settlement of the pier support is plotted.

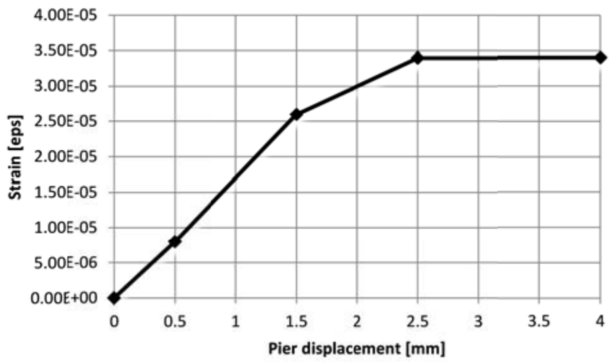

Figure 7. Cumulative measured pier strain related to the first five settlement steps.

4 DATA ANALYSIS AND ASSIMILATION

The first step of the data analysis consisted of an experimental modal analysis. It was decided to employ two techniques working in the time domain due to the great spectral resolution they offer and their modal uncoupling capability. The Eigenvalue Realization Algorithm (ERA) was used to analyse the free decay responses, whilst ambient vibration signals called for a Stochastic Subspace Identification (SSI).

4.1 *Modal parameters and symptoms evolution*

The estimation of both natural frequencies and dampings did not show a monotonic trend during the different campaigns. Figure 8 shows the trend of the first four natural frequencies. It is noteworthy that, whilst in second campaign the trend of the first frequency is almost monotonic and highlights stiffness degradation (mainly related to the boundary conditions of the pier); in the third campaign the interpretation of the curve is more complex. Firstly, the first frequency increased up to 19.23 Hz, this meaning that relaxation made pier settle, increasing the boundary condition stiffness. In fact, after DS 4, the pier was almost completely suspended. Secondly, this phenomenon governs mainly the first modal shape, as it can be seen from 2nd and 4th natural frequencies which retain their values almost equal between the 2nd and the 3rd campaign.

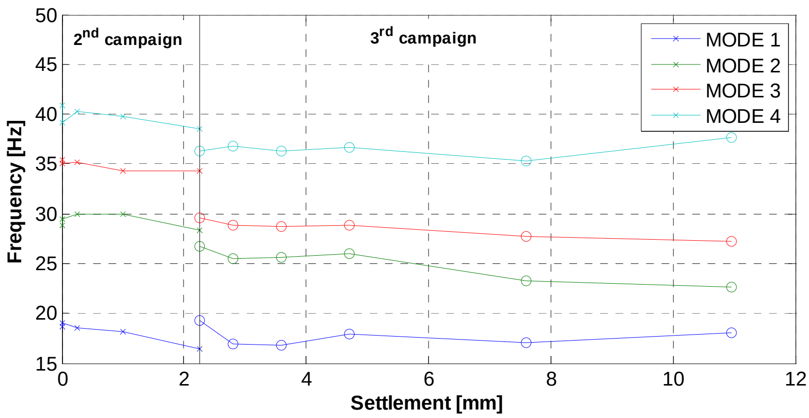

Figure 8. Natural frequencies of the first 4 modes through the various damage steps (damage step 0 corresponds to the healthy state of the bridge). Left side: 2nd campaign. Right side: 3rd campaign.

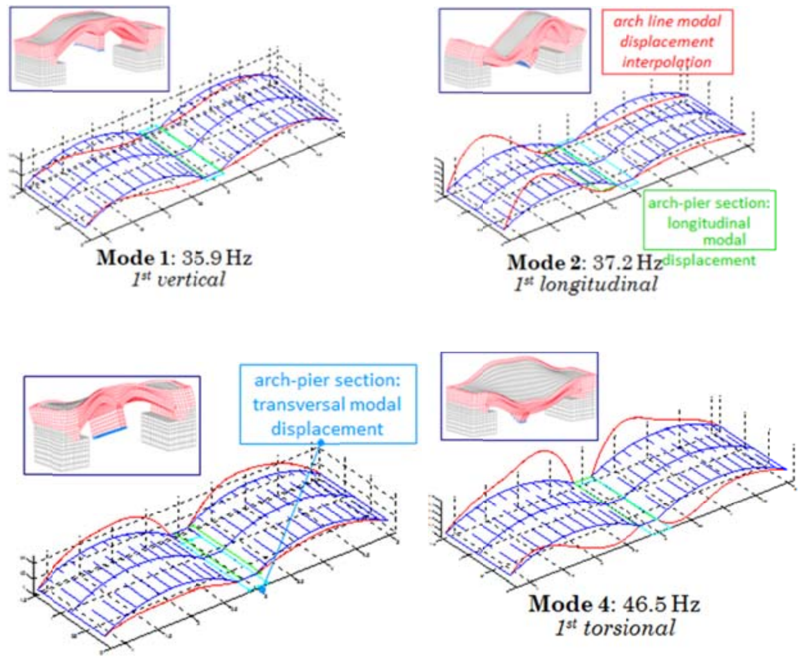

Figure 9. Experimental and numerical modal shapes.

4.2 *Study of the transient after the application of settlements*

Diagrams such as those represented in Figure 8 pose important problems about the real capacity of current diagnostic tools to distinguish between changes in linear parameters induced by damage and other rheologic and indirect actions, including relaxation, ageing etc. In order to derive information about the evolution of the modal parameters throughout the settlements application, the dynamic response was represented in the time-frequency domain by the Choi-Williams transform (Choi and Williams 1989). A non-stationary behaviour was detected relatively to highly coupled modes in the high frequencies range.

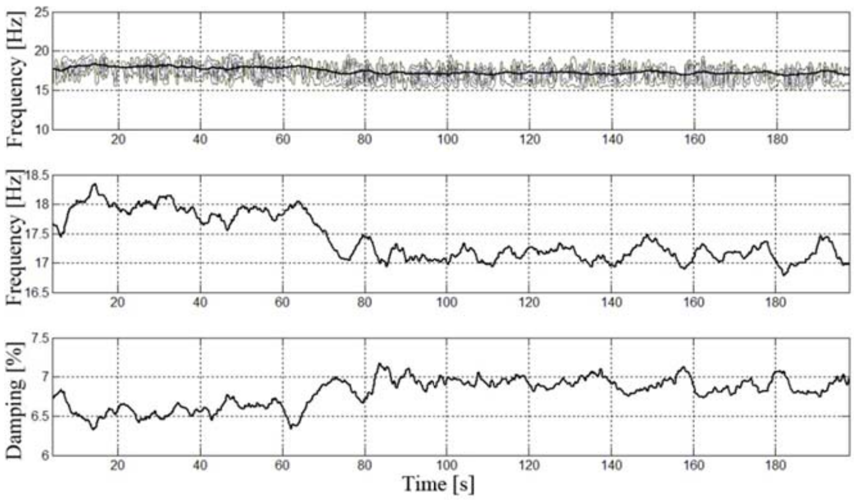

Figure 10. Results of the curve-fitting procedure for the first vibration mode: Spectrogram of a filtered signal (top), modal frequency istantaneous estimate (middle), damping istantaneous estimate (bottom).

In order to further investigate the transient phenomena, an instantaneous estimation of the modal parameters associated with the Frequency Response Function (FRF), was carried out. The implemented methodology follows the optimisation procedure proposed by Ceravolo in (Ceravolo 2004). Figure 10 shows the results of the curve fitting procedure used to calibrate the modal parameters estimates. This allowed detecting the decreasing and increasing variation of the natural frequency and the damping ratio of the first identified mode, respectively. The increase in relative damping here is fictitious, being associated to the assumption of viscous damping.

4.3 *Non-linearity tests*

The tests conducted with the electro-dynamic shaker allowed investigating the presence of non-linear phenomena. Interesting results were found in the resonance tests with different excitation levels. Figure 11 clearly shows the presence of super-harmonics in the resonance test of the first natural frequency, which become particularly intense at the higher sine-excitation test (100 N).

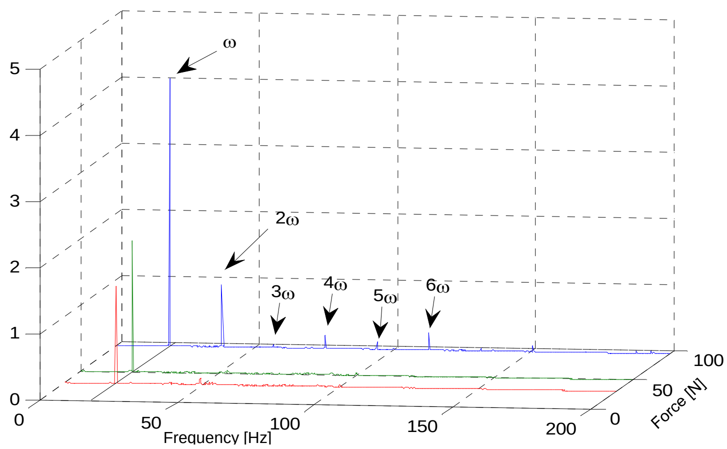

Figure 11. Super-harmonics of the first natural frequencies manifest themselves at higher excitation levels.

These non-linear effects will be subject of further studies, such as non-linear identification using an evolution of a recently developed technique (Ceravolo et al. 2010). In order to characterise the non-linear behaviour of the bridge, a static test will be performed in the same locations where the shaker was used. This will allow quantifying the tangent stiffness matrix related to an associated theoretical oscillator.

4.4 *Structural health monitoring*

A SHM methodology was developed using Outlier analysis (Worden et al. 2000); in order to exploit its limited computational effort, the damage sensitivity and the results accuracy. The choice of a data-driven approach to the damage detection was forced by the complexity and uncertainties of the structure which prevented to define a reliable numerical model and the difficulties to incorporate the noise effects which are unavoidable in the vibration measurements. Several outlier analyses were carried out both in the time and in the frequency domain (Ruocci 2010). An on-line Outlier analysis procedure was also developed and the flow-chart of its algorithm is presented in Figure 12.

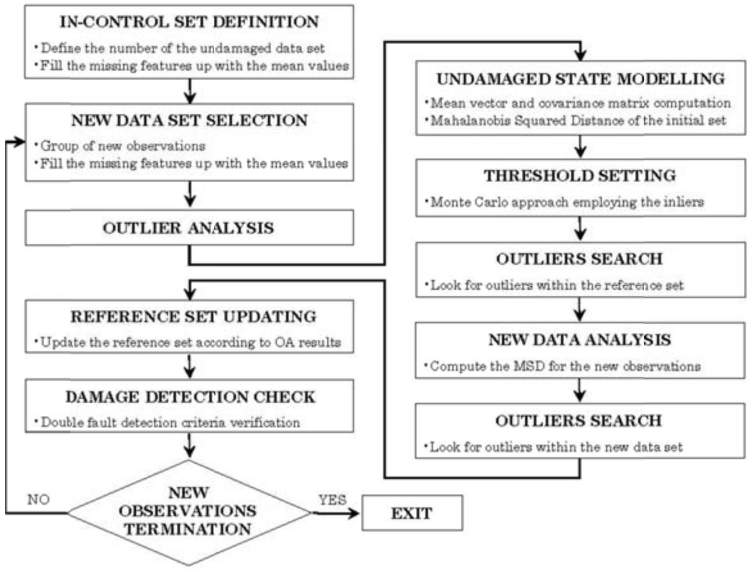

Figure 12. On-line Outlier Analysis methodology pursued.

By way of example, Figure 13 shows the result for the Outlier analysis carried out on the measurements of the second campaign. The acquired signals were analysed in the frequency domain in terms of transmissibility functions. Small portions of the spectra were selected by means of a genetic algorithm and used as inputs to compute the statistical distance assumed as damage index. All the sets concerning the measurements acquired after the introduction of the settlement steps are above the threshold which defines the in-control field. This result proves the accuracy of the damage detection method and the sensibility of the selected features.

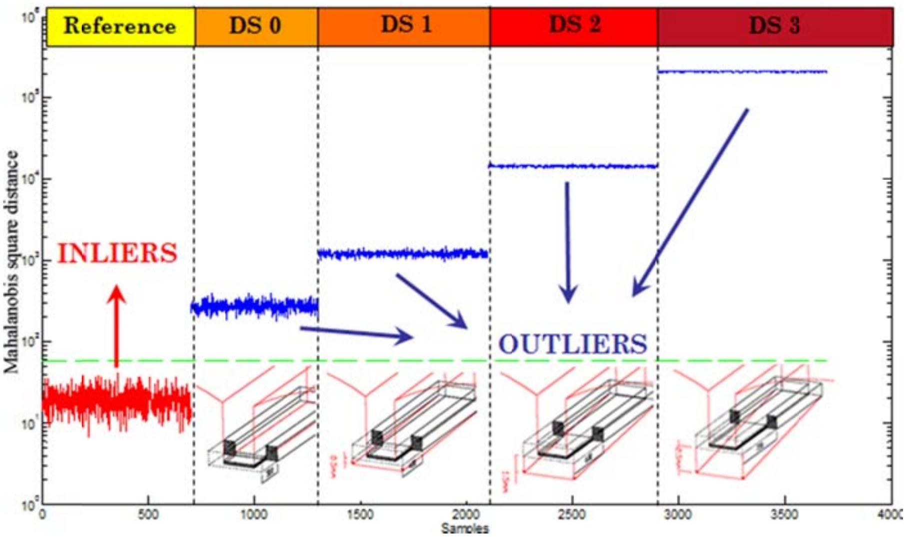

Figure 13. Results of Outlier Analysis.

5 CONCLUSIONS AND PERSPECTIVES

The paper has documented the extensive test campaigns carried out on a scaled masonry arch bridge subject to progressive damage steps. The experimental tests covered the span of three years and the data analysis is still in progress. The final prospect is the development of new vibration-based SHM approaches. This paper, in particular, describes the whole test programme in its various stages and strives for marking out a definite experimental path, as well as for outlining new plans and perspectives for SHM.

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